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Austral echoes of Shklovsky

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On the occasion of the 100th anniversary of the birth of Iosif Shklovsky, this paper reviews a number of his contributions to astrophysics. As a means of considering the impact of these contributions, the diverse and ongoing connections that these have to current research activities in Australia are examined.

Keywords: History and philosophy of astronomy – ISM: molecules – Planets and satellites: composition – Stars: neutron – Extraterrestrial intelligence

1 Introduction

Iosif Shklovsky (1916–1985) made many fundamental contributions to astrophysics during his career (see, e.g., Gurshtein 2007), and the 100th anniversary of his birth provided the opportunity for a conference to review his work. This paper considers a subset of Shklovsky's work in the context of ongoing research. While this paper focuses on activities being carried out in Australia, analogous work is of course being carried out in many other places.

2 Spectral-line radioastronomy

The beginnings of radio-astronomy are well known: Jansky, working for Bell Labs, discovered extraterrestrial radio emission (Jansky 1933); Reber built his own radio telescope to follow up Jansky's discoveries and managed, despite some struggles, to bring it to the attention of the astronomical community (Reber 1940, 1944, 1958). Oort was one of the first to recognise the importance of the work, and he set van de Hulst the task of determining whether there were any spectral lines in the radio band. Van de Hulst (1945) predicted that the spin-flip transition of neutral hydrogen would emit a line at 21.2 cm, or around 1410 MHz.

Reber (1958) recounts that he met van de Hulst in 1945 to discuss the prospects for detecting this line. Reber started on preparations to attempt this, but no observations were made before observing from Wheaton ended in 1947.

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The use of atomic beam magnetic resonance techniques allowed the frequency of the hyperfine transition to be measured in the laboratory by Nafe et al. (1947), then with increasing precision by Nagle et al. (1947) and Nafe and Nelson (1948).

Shklovsky, who had completed his doctorate at Moscow State University in 1949 on work related to the solar corona, became interested in the question of spectral lines in radioastronomy, publishing three pioneering works in this field: "Monochromatic radio emission from the galaxy and the possibility of its observation" (Shklovsky 1949), "Galactic radio-spectroscopy" (Shklovsky 1952), and "The possibility of observing monochromatic radio-emission from interstellar molecules" (Shklovsky 1953).

In the first, Shklovsky discussed the potential for detecting the HI line, including the possibility of deuterium, and further considered the prospects for observing spectral lines associated with simple molecules: OH, CH, CH^+, and NH. Although Shklovsky cites the HI frequency of Nafe et al. (1947) it appears that while aware of this results he had not seen the actual paper, as although Nafe et al. also measured the corresponding frequency for deuterium (327 MHz, $\lambda = 92$ cm) Shklovsky refers to it as the $\lambda = 84$ cm line.

The second paper follows the discovery of the 21cm HI line (Ewen and Purcell 1951, Muller and Oort 1951, Pawsey 1951) and is primarily concerned with the potential for further observations of hydrogen and deuterium. Shklovsky acknowledged these lines would be weak and that detailed studies would require a large antenna, of ∼40 m diameter – much larger than Reber's 10 m dish or the 7.5 m Würzburg antennas being pressed into service. However, he noted the existence of the 66 m Jodrell Bank transit telescope (Brown and Hazard 1950), then the largest reflector in the world, which was used to discover radio emission from M31 (Andromeda) and offered promise that these lines would be detectable.

The third follows more detailed calculations and makes predictions for the frequencies of expected spectral lines, which are discussed in more detail in the following subsections.

2.1 OH molecules

Shklovsky's earliest prediction for the Λ-doubling line of OH was $\lambda = 9.52$ cm, with the observation that the line would be of a similar strength to the 21cm line of H I (Shklovsky 1949). This was quickly refined, with Shklovsky (1953) deriving a frequency of 1645 MHz. By the time of the review of Townes (1957) the main lines were expected to be around 1665 and 1667 MHz. Early searches were unsuccessful (Barrett & Lilley 1957) but were reduced in sensitivity by having to search a relatively wide bandwidth with effectively a "single channel spectrometer", as the line frequencies were not accurately known, This changed with the laboratory measurement of the main lines by Ehrenstein et al. (1959), which allowed the astronomical detection of the main lines of OH at 1665 and 1667 MHz (Weinreb et al. 1963, Bolton et al. 1964).

The satellite lines of OH (1612 and 1720 MHz) soon followed. In an informal account given at the thirtieth anniversary of the Parkes radio telescope, Robinson (1994) recounted: "We also knew, from theory, that there should be two more OH lines besides the two seen by Weinreb and Barret, and confirmed by us. No-one knew their frequencies. But the strong absorption in the Galactic centre and easily

recognisable pattern of the absorption made it possible for us to go hunting for the other two lines."

However the formal account of Gardner et al. (1964) reveals that it was a more systematic approach that produced success: "Barrett and Lilley had originally predicted frequencies of 1632 and 1700 Mc/sec for these lines. However, a brief search of the spectrum of Sagittarius-A near 1632 Mc/sec produced no positive result. On the basis of improved constants from Radford's laboratory measurements, Posener computed frequencies of 1612 and 1720 Mc/sec for the satellite lines."

Despite this significant contribution, Posener's name is not well known in astronomy. Desmond Posener (1921–2003) graduated from the University of Sydney and completed a PhD at MIT on the microwave spectrum of the water molecule, under the supervision of Malcom Strandberg. He then returned to Australia and a position with the CSIRO Division of Applied Physics, but made no further contributions to astronomical research.

2.2 OH masers

In 1964, the Nobel Prize in Physics was awarded "for fundamental work in the field of quantum electronics, which has led to the construction of oscillators and amplifiers based on the maser-laser principle." The Prize was shared by an American, Charles Townes, a Russian, Nicolay Basov, and an Australian, Aleksandr Prokhorov! (Prokhorov was born in 1916 in the Australian state of Queensland and lived there until his family returned to Russia in 1923 so, despite his secondary and tertiary education and the research leading to his award all taking place in the Soviet Union, Australians will claim him as their own!)

Despite this, when astronomical OH masers were discovered by Weaver et al. (1965), they were not recognised as such, being initially dubbed "mysterium". Robinson (1994) describes how the discovery of OH masers could have been made earlier, but was missed, at Parkes. Such an unexpected development naturally attracted broad interest, with Shklovsky's contribution being a consideration of the nature of OH masers (Shklovsky 1969).

Studies of OH are continuing to shed light on the physical conditions in stellar environments and the ISM. Green et al. (2012) describe a pilot project undertaken with the Australia Telescope Compact Array to determine whether Galactic magnetic fields can be traced with Zeeman splitting of OH masers associated with high-mass star formation (Fig. 1). Eleven Zeeman pairs were found across six sites of high-mass star formation. Magnetic field strengths between 1.5 and +3.8 mG are inferred from the data, with the detection rate and consistency of the direction of the magnetic fields boding well for a full Galactic survey.

While the Green et al. pilot study was targeted at 6.7 GHz methanol masers, tracers of high mass star formation, the Southern Parkes Large-Area Survey in Hydroxyl (SPLASH) is an unbiased and fully sampled survey of the southern Galactic plane in all four OH ground-state transitions. Initial results, presented by Dawson et al. (2014), revealed that diffuse OH is widely detected in all four transitions, and that departures from local thermodynamic equilibrium are common even in the 1665- and 1667-MHz main lines. Masers were detected in all four transitions, approximately half of which were new discoveries, and associated with a range of objects, indicating that

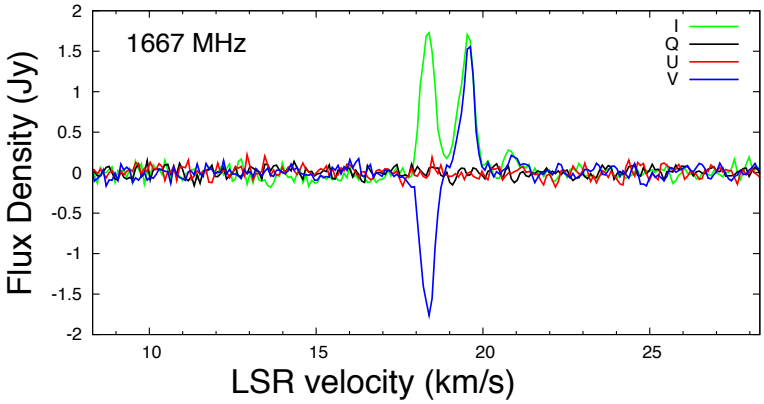


Figure 1 Stokes I, Q, U and V for the OH maser 291.610−0.529, illustrating the Zeeman splitting of the 1667 MHz main line, from the pilot study of Green et al. (2012).

SPLASH will produce a substantial increase in the known population of ground-state OH masers in the southern Galactic plane, and auguring well for the larger GASKAP project (Dickey et al. 2013) with the Australia Square Kilometer Array Pathfinder.

2.3 CH

CH was the first molecule detected in interstellar medium – at optical wavelengths (Dunham 1937). Shklovsky (1949) considered it as a candidate source of radio spectral lines, and predicted (Shklovsky 1953) a frequency of 3.18±0.01 GHz. Despite subsequent predictions of 3030^{+60}_{-30} MHz (Goss 1966) and 3374±20 MHz (Baird and Bredohl 1971), the line eluded detection (Cato et al. 1972) until it was discovered by Rydbeck et al. (1973) at 3.335 GHz together with satellite lines at 3.264 and 3.349 GHz. This was soon followed by detections at Parkes in both absorption and emission by Robinson et al. (1974) and Gardner et al. (1974).

Studies of CH are continuing at Parkes: in 2003, a new 10 cm/50 cm dual-band receiver was installed at Parkes providing simultaneous coverage of the 2.6–3.6 GHz, and 650–710 MHz bands. While primarily designed for pulsar observers, with the dual bands enabling accurate determinations of pulsar dispersion measures, the 10 cm band also allows the CH lines to be studied (Mader, in prep.). In 2009, the 50 cm band was changed to 700–760 MHz in an attempt to reduce the impact of radio-frequency interference, and enabling CH lines in this band to also be observed.

2.4 Deuterium

Shklovsky (1949) was the first to consider the hyperfine transition of deuterium in addition to that of hydrogen in an astronomical context. Deuterium has a natural abundance in the Earth's oceans relative to hydrogen of 1:6500, but measurements of its abundance in other astronomical environments are of interest. As mentioned earlier, Shklovsky (1949, 1952) initially predicted this line at a wavelength of 84.5 cm, with laboratory measurements determining the wavelength to be 92 cm. An early



Figure 2 The "hole in the ground" antenna used by Stanley and Price (1956) to search for the hyperfine transition of deuterium, predicted by Shklovsky. (Image courtesy CSIRO.)

claim for the detection of the line was made by Getmanzev et al. (1957), which inspired efforts to confirm this in Australia (Stanley and Price 1956), the UK (Adgie and Hey 1957) and the USA (Weinreb 1962), all of which were unsuccessful.

Stanley and Price (1956) used the "hole in the ground" antenna at Dover Heights, pictured in Figure 2. The 21.9 m (72-foot) antenna was modelled on the 218-foot (66 m) transit telescope mentioned earlier, and is described in more detail by Bolton (1982) and Orchiston & Slee (2002). The 92 cm line was finally detected by Rogers et al. (2005, 2007) with a small electronically-steered array of crossed Yagi antennas. In the interim, studies of the deuterium abundance in the local interstellar medium were advanced by the launch of the far-UV FUSE mission, which allowed direct detection of D I Lyman series transitions (Moos et al. 2002).

3 PKS 1934–638

Bolton et al. (1963) reported the discovery of PKS 1934−638, now recognised as an archetypal giga-hertz peaked spectrum (GPS) source. The source is bright (15 Jy at 1.4 GHz) and appears to display minimal variability, resulting in its adoption as the primary flux density calibrator of the Australia Telescope Compact Array. Shklovsky (1965) considered the source and, based on his success in predicting a decline in the flux density of Cas A (Shklovsky 1960), suggested a similar behaviour for PKS 1934−638.

Véron-Cetty et al. (2000) revisited this, noting "Long ago Shklovsky (1965) predicted, soon after its discovery, that PKS 1934−638 should diminish in flux quite rapidly, if an expanding source. It was found however to be quite constant (being used now as an Australia Telescope standard: perhaps imprudently?) and therefore it should be located in a high pressure medium that confines it."

Kellermann (1966) extended the work of Bolton et al. and considered the possibilities for the peaked-spectrum, including the suggestion of Kardashev (1964) that a peaked-spectrum source may be an artificial transmission from an intelligent civilization.

4 Pulsars

The discovery of the first pulsar was reported by Hewish et al. (1968). Richards and Comella (1969) observed that the 33 ms period of the Crab pulsar ("NP 0532") was increasing by 36 ns per day. Shklovsky joined the debate about the origin of this effect, quickly detected in other pulsars too, in his paper "Possible Causes of the Secular Increase in Pulsar Periods" (Shklovsky 1970). Shklovsky considered a number of possibilities, including gravitational radiation, also pointing out that there is a simple geometrical effect that would be detectable if pulsars are moving at high velocity. In their detection of proper motion for PSR 1133+16, Manchester et al. (1974) found this effect amounted to about 5% of the observed period derivative for the adopted pulsar distance (see also Manchester and Taylor 1977).

Bell and Bailes (1996) pointed out that this also applies to the orbital period of wide pulsar binary systems: "Any acceleration of a pulsar along the line of sight will change the observed pulse period derivative, $\dot{P}$. As Shklovskii (1970) pointed out, an apparent acceleration occurs when the proper motion is significant" (see also Kopeikin 1996). This was first measured for the PSR J0437−4715 binary system by Verbiest et al. (2008), who gave the effect the name now in common usage: "...the dominant kinematic contribution [is] known as the Shklovskii effect (Shklovskii 1970), an apparent acceleration resulting from the nonlinear increase in radial distance as the pulsar moves across the plane perpendicular to the line of sight." Verbiest et al. used the Shklovsky effect to determine a kinematic distance of 157.0±2.4 pc, a significant improvement over the tradition parallax distance of 150±12 pc, and this was refined even further by Reardon et al. (2016). Yao et al. (2017) state that the Shklovsky effect has now provided the most precise distance estimate for three pulsar systems.

5 SETI

Shklovsky and Sagan are widely known for their work on the possible existence of extraterrestrial intelligence. Shklovsky (1991) noted that his interest in this field came about in October 1961, when monographs were solicited to celebrate the fifth anniversary of the launch of Sputnik: "An idea popped into my head. I said that in the given time [manuscripts would have to be finished by July 1962] I could finish

a monograph I had already started (I hadn't!) on the unusual subject of the possible existence of intelligent life elsewhere in the Universe. ... I had been greatly impressed by Cocconi and Morrison's 1959 article discussing the possibilities of radio communications over interstellar distances." The paper of Cocconi and Morrison (1959), "Searching for Interstellar Communications," is a landmark in the history of the search for extraterrestrial intelligence (SETI).

The large aperture of the Parkes telescope makes it an attractive instrument for SETI searches: Blair et al. (1992) describe a narrow-band search of 176 targets, including 166 stars and 7 globular clusters; Shostak et al. (1996) observed three fields in the Small Magellanic Cloud encompassing 10^7 stars in a search for signals that could be ascribed to extraterrestrial intelligence; and Stootman et al. (2000) report on the southern hemisphere component of a commensal search program called SERENDIP. Parkes was also part of the array used for the first VLBI (Very Long Baseline Interferometry) SETI experiment, which observed the star Gliese 581 after the discovery of a planet on the edge of its habitable zone in 2007 (Rampadarath et al. 2012).

In 1995, the Parkes 64 m telescope was used together with the Mopra 22 m telescope as part of Project Phoenix, which observed 209 solar-type stars over the frequency range 1.2–3.0 GHz to search for possible narrow-band transmissions from extra-terrestrial life (see Tarter 1997). More recently, Parkes has entered an agreement with the Breakthrough Foundation for the use of 25% of Parkes observing time for a SETI search comprising observations of the million closest stars, 100 closest galaxies, and a survey of the galactic plane (Isaacson et al. 2017).

6 Phobos

The two satellites of Mars, Phobos and Deimos, were discovered in 1877. Both are relatively small (∼20 km across) and of low density. Shklovsky is remembered (Gurshtein 2007) for his suggestion that the low density of Phobos indicated it might be a hollow spacecraft. In further discussing his plans for his book on SETI, mentioned in the previous section, Shklovsky (1991) continued: "The futurological aspects of the book were easier to deal with: I could use my natural bent for fantasy. Even my notorious "artificial satellites of Mars," which had kicked up such a fuss in 1959, would come into the picture." (It is tempting to conclude that this suggestion was inspired by the Cocconi and Morrison paper, which was published in the 19 September issue of Nature that year, but it has not been possible to determine when Shklovsky's suggestion was made.)

The nature of Phobos was able to be studied in more detail on 28 December 2013 when the Mars Express spacecraft made a close fly-by, only ∼45 km from the surface of the satellite. A global array of radio telescopes, including the Australia Telescope Compact Array, and the Hobart, Ceduna and Yaragadee telescopes, used the VLBI phase-referencing and Doppler techniques to reconstruct the spacecraft's trajectory in the vicinity of Phobos with high accuracy, which will help place better constraints on the geophysical parameters of the satellite, and with possible implications for our understanding of its origin (Duev et al. 2016).

7 RadioAstron

As noted by Gurshtein (2007), one of Shklovsky's lasting contributions has been "the education and inspiration of two generations of students." Foremost of these is Nikolai Kardashev: Shklovsky (1991) observed "Kolya was always full of big plans, and amazingly enough he almost always managed to realize them... In addition to Kolya's exceptional natural abilities, high principles, and firm and independent character, he has an element of natural luck to thank for his successes." (This last comment recalls the remark by German scientist Paul Ehrlich that "Success in research requires four Gs: Glück, Geduld, Geschick und Geld." [Luck, patience, skill and money]!)

Kardashev is the Project Director of the RadioAstron mission. Launched in 2011, the Spektr-R satellite is the key element of this space VLBI project, which provides space baselines up to 30 Earth diameters (Kardashev et al. 2013), providing new insights into the nature of active galactic nuclei and the interstellar medium (Smirnova et al. 2014, Lobanov et al. 2015, Gómez et al. 2016, Gwinn et al. 2016, Kovalev et al. 2016, Popov et al. 2017). Radio telescopes in Australia and South Africa are playing a critical role in RadioAstron observations of southern hemisphere targets (e.g., Edwards et al. 2017).

It should not be surprising that Shklovsky also contributed to the possibilities provided by space-based observations, co-authoring the papers "Radio Astronomical investigations with the aid of artificial satellites," (Getmantsev et al. 1958) and "Unlimited extended space radio telescope. I. Scientific problems, composition and characteristics of the complex" (Buyakas et al. 1978).

Conclusions

This paper has viewed Shklovsky's wide-ranging contributions to astrophysics through the prism of subsequent work undertaken in Australia. While this is a somewhat non-standard approach, it has highlighted the depth, breadth and ongoing relevance of Shklovsky's research work. It is unfortunate that English translations of a number of Shklovsky's key early papers are not yet available, as these would help make his legacy more widely appreciated.

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